EFFECTS OF EARTHQUAKE MOTION AND OVERBURDEN THICKNESS ON STRAIN BEHAVIOR OF CLAY AND SANDY SOILS

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Abstract

Effects of earthquakes (EQs) are not limited only to the epicentral region. Depending on the magnitude of the EQ and the frequency content of input motion, the damages can be widespread. The amplitude, duration and frequency content of input motion at a site further changes due to the presence of *in-situ* soil at the site. Thus, similar to the determination of regional seismic hazard, quantification of local site effect is equally important. Dynamic soil properties which determine the behavior of local soil under EQ loading are not readily available on regional level. Hence, standard dynamic soil properties curves developed for other regions are used for a large number of studies. In the present work, response of two soil columns consisting of clay and sand alone throughout the depth, are analyzed using equivalent linear method using 30 worldwide recorded ground motions. Based on the present analysis, two important conclusions are drawn. It is well established fact that in equivalent linear analysis, the response of soil is governed by one value of strain. First conclusion suggests that understanding equivalent linear response of same soil collectively during various recorded ground motions covering a wide range of ground motion parameters, complete nonlinear soil behavior can be understood. In such case each ground motion will provide dynamic soil properties corresponding to specific level of strain. As a second conclusion, it is found that this strain developed in the soil during each ground motion is a function of peak horizontal acceleration (PHA) of input motion as well as the thickness of overburden. Further, this strain governs the soil behavior during that particular ground motion. Thus, if this value of strain is known, the response of the soil can be determined based on one value of shear modulus and damping ratio avoiding iterative procedure. Based on the above analyses, two empirical correlations are proposed in this work, correlating above value of strain in a soil layer with the PHA of input ground motion as well as overburden thickness above the soil layer. Overburden thickness is used in place of overburden pressure since it is used in available ground response models while determining the value of strains. Knowing the PHA from seismic hazard study and overburden thickness from soil investigation, one value of strain can be estimated based on proposed correlation. The behavior of soil will be governed by this value of strain alone and thus considering complete nonlinear soil behavior may not be needed. It has to be highlighted here that the present work uses two hypothetical soil columns of sand and clay respectively to provide a general idea about the above two conclusions. For case specific correlations however, similar works can be attempted in the future.

Keywords: Local site effects, dynamic soil properties, input motion, overburden thickness, strains.

1. Introduction

It is a widely recognized fact that the characteristics of EQ ground motion at any site is influenced by the seismic source, path and local site effect. Modification of the incoming seismic waves by the soil layers, known as local site effect has a profound impact on the damages that occur during an EQ [1]. This phenomenon is attributed to the reverberations and trapping of the seismic waves travelling through soil layers [2]. These soil layers alter the amplitude, the frequency content and the duration of ground motion between the bedrock and the surface. The modification of ground motions by local soil is a major cause for the induced effects such as landslides, liquefaction and amplified ground shaking [3]. The study of local site effect gained importance following the 1985 Michoacan EQ which caused severe damages at several locations in Mexico City, situated about 360km away from the epicenter. During the 1985 Michoacan EQ, ground motions between the bedrock and the surface were amplified by a factor of 50 for the frequencies between 0.25 and 0.7Hz [4]. Larger values of amplification were observed at sites having very soft clay layer of lacustrine origin [5]. Further, the effect of local soil was evident during the 1989 Loma Prieta EQ, which caused tremendous damages in San Francisco-Oakland region, located about 80km away from the epicenter. On 7th April 2011, the country of Japan was hit by a great EQ (Mw-9.0) with the epicenter located 130km east coast of Sendai in the Pacific Ocean. This was the biggest EQ ever recorded in Japan. Large amount of liquefaction and uneven settlements were observed during this EQ in the city of Maihama and Tokai Mura located beyond 150km from the epicenter [6]. The 2001 Bhuj EQ (Mw=7.7) is an excellent example where the local site effect played an important role in triggering damages at various sites. Amplification of ground motions by the soil layers caused severe damage in major cities such as Ahmedabad, Bhuj, Rajkot, Anjar and Gandhidham regions spreading over 350km away from the epicenter [7]. The dams at Fategadh, Kaswati, Suvi, and Tapar, built on alluvial soil were damaged in the 2001 Bhuj EQ [8]. The 1991 Uttarkashi EQ (Mw=6.8) and 1999 Chamoli EQ (Mw=6.5) also showed similar damage patterns at sites far from the epicenter. Regions along the bank of Alakananda River within the Chamoli town were damaged severely in the 1999 Chamoli EQ. The same EQ event caused structural damages even in New Delhi and Dehradun, located 200km from the epicenter [9]. The 2011 Sikkim EQ (Mw=6.9) reported considerable damage to buildings in northern parts of Bihar, eastern Nepal, southern Bhutan and parts of Tibet located several hundreds of kilometers away from the epicenter [10]. This EQ event also triggered massive landslides in Mangan, Chungthang etc. areas located in north Sikkim even though the size of the EQ was moderate [11]. Examples mentioned above and many more are clear indications that the majority of the damages are not only in the epicentral region but at farther distances as well during a moderate to major EQ event due to the presence of local soil. Hence, effective estimation of local site effect is an important factor in understanding the surface ground motion scenario and the possible extent of induced damages during an EQ.

Several studies on the estimation of local site effect for various regions have been carried out by various researchers. Site effects at Jabalpur, India were assessed by Geological Survey of India, the National Geophysical Research Institute, the Indian Meteorological Department, etc. by performing geological, geotechnical, geophysical and seismological tests [12]. According to Rao et al [12], amplification of the ground motion signals in the range of 4.0 to 6.0 was found within the frequency range of 4–5Hz. These amplifications were seen mostly in the north-western part of Jabalpur having 30 to 50m of thick alluvial deposits. With similar objective, numerous researchers attempted site specific response studies worldwide [13, 14, 15]. Any site response study requires two important inputs namely; regional ground motion records and dynamic properties of soil. However, in majority of the studies, either one or both of the above inputs are not available at regional level. In such cases, selection of ground motions and dynamic soil properties from other regions is commonly practised. In the present study, an attempt is made to show that the *in-situ* soil response obtained from a site response study is an indirect representation of selected dynamic soil properties and not the regional characteristics of *in-situ* soil at the selected site.

2. Soil Columns

The importance of local soil upon amplifying bedrock motion evidenced during various EQs has been discussed earlier. The objective of present study is to assess the impact of selected dynamic soil properties from one region and using the same for site response analysis of other regions. In absence of regional soil dynamic properties available, site response analysis by selecting dynamic soil properties from other region in conjunction with *in-situ* subsoil properties is carried out and outcomes are known as site specific findings. A subsoil deposit at any site may consists of different soil types available in variable thickness. In the present analysis, soil columns of either sand or clay, are selected. Interpretation of soil columns with varying soil types at various depths is difficult at this stage and can be attempted in future. Previous studies where same type of soil was used for site response analyses are also available. These include site response analyses conducted by Vucetic [16] considering same soil type (sandy or clayey with various range of PI) to study the effect of soil type upon ground motion amplification. Similarly, Ishibashi and Zhang [17] and Park and Stewart [18] analyzed boreholes consisting only of clay or sandy soils respectively to propose empirical correlations between damping ratios (D) and shear modulus (G_{sec}). In another work, Afacan et al [19] conducted site response study based on centrifuge testing on soft clays. Taking into account the actual field conditions also suggests that many parts of central India consist of clayey deposits while regions in Indo-Gangetic Basin predominantly consist of sandy deposits. Thus, with the support of previous studies available with same soil type throughout the borehole depth, the present study analyzes the response of soil columns consisting of sand and clay with PI=0. Since the present work is based on equivalent linear analysis, the depth of soil columns is restricted to 15m. For deeper soil columns, nonlinear soil behavior will be affected by the overburden pressure which cannot be captured using equivalent linear analysis [20]. Deeper soil columns with similar analysis however, can be attempted in future. Variation in N-SPT values with depth in the boreholes are considered in the range of 5 to 25 in accordance with the borelog considered for Ahmedabad, Chennai, Mumbai, Chamoli and Lucknow respectively [21, 22, 23, 24, 25]. It has to be highlighted here that borelog by Govindraju et al [21] also showed complete deposit of sand alone till a depth of 15m. Similarly, borelog by Anbazhagan et al [25] showed the presence of clay alone till 15m depth. In coherence with these studies and many more, two soils columns of sand and clay are modelled in SHAKE2000 [26] for the present work. For the analysis, each soil column is divided into sub-layers having maximum thickness of 3m having same soil type and above discussed N-SPT variation with depth.

3. Selection of input motion

Input motion is another important parameter for any site response analysis defining the seismic hazard at bedrock level at that site. In the absence of regional ground motion records, ground motions such as during 1940 El-Centro EQ, 1985 Mexico EQ, 1989 Loma Prieta EQ, 1994 Northridge EQ, 1995 Hyogoken-Nanbu EQ, 1999 Chi-Chi EQ etc. are used from the worldwide database such that selected ground motion may reflects the actual seismic hazard of the site under consideration. In the absence of regional ground motion records however, ground motion characteristics for future EQ at the site of interest cannot be approximated by selecting single ground motion from the worldwide database [1]. Highlighting the dependency of ground motion amplification upon the bedrock motion characteristics, Kumar et al [1] performed site response analysis of 41 soil columns considering 30 globally recorded ground motions covering a wide range of ground motion characteristics.

Table 1: Ground Motion properties of the selected input motions (Ref: [1])

Sr. No.	Ground Motion details as per SHAKE2000	Epicentral Distance (km)	Mw	PGA (g)	Duration (s)	Predominant Frequency (Hz)
1	ADAK, ALASKA 1971-M 6.8;R-67KM, N81E	86.77	6.8	0.098	24.58	8.33
2	ANCHORAGE, ALASKA 1875, M-6, R81-GOULE HALL STATION	81.93	6.0	0.036	18.59	10.00
3	ANCHORAGE ALASKA 1975, M 6, R 79, WESTWARD HOTEL STATION (BASEMENT)	78.37	6.0	0.049	38.96	7.14
4	ANZA 02/25/80, BORREGO AIR BRANCH 225	43.1	5.3	0.046	10.25	3.85
5	ANZA 02/25/80 1047, TERWILLIGER VALLEY 135	15.8	5.3	0.080	10.01	16.67
6	BISHOP-ROUND VALLEY 11/23/84 1914, MCGEE CREEK SURFACE 270	42.35	5.8	0.075	6.80	12.50
7	BORREGO MOUNTAIN 04/09/68 0230, EL CENTRO ARRAY 9, 270	60.0	6.4	0.056	39.95	39.95
8	BORREGO MOUNTAIN 04/09/68 0230, PASADENA-ATHENAEUM, 270	216.8	6.4	0.009	60.23	1.22
9	BORREGO MOUNTAIN 04/09/68 0230, TERMINAL ISLAND, 339	205	6.4	0.008	51.80	2.50

Table 1 (conti): Ground Motion properties of the selected input motions (Ref: [1])

10	CAPE MENDOCINO EARTHQUAKE RECORD 04/25/92, MW-7.0, 90 DEG COMPONENT	10.0	7.1	1.03	59.98	50.00
11	CHALFANT 07/20/86 1429, BISHOP PARADISE LODGE,070	19.8	6.4	0.046	39.95	16.67
12	CHILE EARTHQUAKE, VALPARAISO RECORD, 3/3/85	129.2	7.8	0.120	79.39	16.67
13	COALINGA 05/02/83 2342 PARKFIELD, FAULT ZONE 6/ 090	43.9	6.5	0.055	39.95	8.33
14	COALINGA 05/09/83 PALMER AVE ANTICLINE RIDGE, 090	12.5	5.3	0.215	40.00	10.00
15	GEORGIA, USSR 06/15/91 0059, BAZ X	49.0	6.2	0.033	34.07	4.55
16	IMPERIAL VALLEY 10/15/79 2319, BONDS CORNER 230	15.9	5.0	0.100	19.885	5.56
17	KERN COUNTY 7/21/52 11:53, SANTA BARBARA COURTHOUSE 042	80.5	7.5	0.086	75.35	4.17
18	KOBE 01/16/95 2046, ABENO 000	24.9	6.9	0.22	139.98	5.00
19	KOBE 01/16/95 2046, KAKOGAWA 000	22.5	6.9	0.250	40.91	12.50
20	KOBE 01/16/95, KOBE PORT ISLAND 090	0.9	6.9	0.530	42	2.50
21	LIVERMORE 01/27/80 0233, HAYWARD CSUH STADIUM 236	33.9	5.8	0.027	15.98	3.13
22	LIVERMORE 01/27/80 0233 LIVERMORE MORGAN TERR PARK 265	20.6	5.8	0.197	24	5.56
23	LOMA PRIETA TA 10/18/89 00:05, ANDERSON DAN DOWNSTREAM 270	16.9	7.0	0.240	39.59	5.00
24	LOMA PRIETA TA 10/18/89 00:05, HOLLISTER DIFF ARRAY 255	13.9	7.0	0.270	40	1.92
25	MICHIOACAN EARTHQUAKE 19/9/85, CALETA DE CAMPOS, N-COMPONENT	38.36	8.1	0.140	81.06	2.27
26	NORTHERN CALIFORNIA 09/22/52 1141, FERNDALE 134	44.3	5.2	0.070	40	5.00
27	NORTHRIDGE EQ 1/17/94 1231, ANACAPA ISLAND	71.4	6.7	0.013	40	25.00
28	NORTHRIDGE EQ 1/17/94 1231, ARLETA 360	9.5	6.7	0.310	39.94	16.67
29	PARKFIELD 06/28/66 04:26, CHROME # 8	11.2	6.1	0.116	26.09	25.00
30	TRINIDAD 11/08/08, 10:27, RIO DEL OVERPASS E	72.0	7.2	0.130	22	3.13

Selected ground motions also incorporated the seismic activity of nearby as well as distant sources as per Kumar et al [1]. In the present analysis as well, 30 ground motions selected by Kumar et al [1] are used for the analysis as shown in Table 1. Selected ground motions show a wide range of predominant frequencies from 1.2Hz to

50Hz, PHA from 0.008g to 01.03g and duration variation from 6.8s to 139.98s. All these ground motions are obtained from PEER database as given in SHAKE2000.

4. Dynamic Soil properties

Response of a soil deposit to EQ generated ground motion is a function of dynamic properties. These include the G_{sec} and D. Both, G_{sec} and the D are dependent on the shear strain (Υ). The value of G_{sec} is normally defined as the slope of a secant line on a stress-strain curve that connects the extreme points on a hysteresis loop at a given Υ as shown in Fig 1. The variation of G_{sec} with Υ is represented by modulus reduction (G_{sec}/G_{max}) curve obtained by dividing the G_{sec} at various values of Υ by the maximum value of G_{sec} (G_{max}) at very small shear strains (less than or equal to 10^{-4}%). The value of D on the other hand, can be determined from the area under stress-strain curve in a hysteresis loop corresponding to Υ. Plot of D versus Υ over a wide range of Υ is known as the damping curve. Both, G_{sec}/G_{max} and damping curves for a known soil type can be obtained from different laboratory tests such as simple shear, torsional shear, cyclic tri-axial, resonant column tests etc. [27]. However, often it is very difficult to determine G_{sec}/G_{max} and damping curves for regional soils due to non-availability of necessary experimental facilities and various complications in conducting the above tests. Due to this reason, for a majority of regions globally, G_{sec}/G_{max} and damping curves at regional level are not available. In the absence of regional level G_{sec}/G_{max} and damping curves, most of the site response studies use standard G_{sec}/G_{max} and damping curves developed for specific regions [1]. Such standard curves are available for various types of soil depending on parameters such as over consolidation ratio (OCR) or plasticity index (PI) or any other properties which resemble that soil type. SHAKE2000 which is an equivalent linear ground response tool consists of

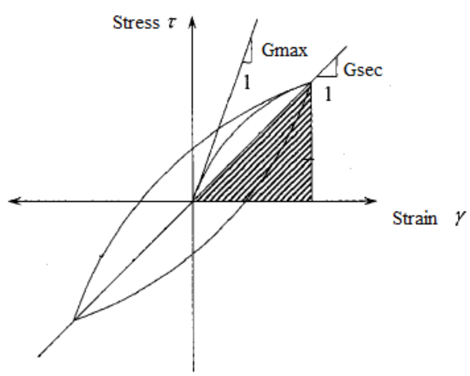

Fig 1- Typical hysteresis loop for one cycle of loading

database having G_{sec}/G_{max} and damping curves for various soil types proposed by various researchers.

For the present analysis, G_{sec}/G_{max} for average sand and clay with PI=0, are taken as per Seed and Idriss [28] and Sun et al [29] respectively. Similarly, the damping ratio curves for sand and clay proposed by Seed and Idriss [28] are used in this work as shown in Fig 2 after Kumar et al [1]. G_{sec}/G_{max} and damping curves were developed by Seed and Idriss [28] for sandy soil based on a large number of laboratory and field tests on sand from California region. Similarly, Sun et al [29] studied G_{sec}/G_{max} ratio of clay with different PI with over consolidation ratio (OCR) of 5–15. Based on the work, Sun et al [29] found that a low value of PI has considerable effect on the position of G_{sec}/G_{max} curve when compared with high PI clays. Based on the work, Sun et al [29] proposed different G_{sec}/G_{max} curves for clay with different PI. For the present analysis, clay with PI=0 is only considered. For rigid halfspace, dynamic soil properties as per Schnabel [30] are used in accordance with the study by Kumar et al [1]. Study based on other values of PI can also be attempted in future.

5. Analysis and results

In order to perform equivalent linear analyses using SHAKE2000, each of the 15m sand and clay columns are modelled. The base of soil column is modeled as rigid half-space for the entire analysis. Since the study is not

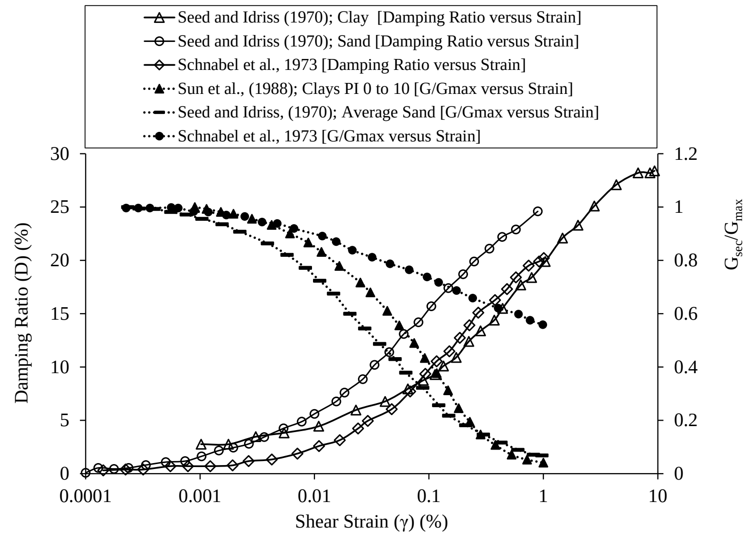

Fig 2- Dynamic soil properties used for the present analysis

region specific, built-in correlation between G_{max} and N-SPT proposed by Seed et al [31] available in SHAKE2000 is used in the present analysis. Each of the two soil columns is subjected to all the 30 ground motions selected above. Outputs in the form of stress time history and strain time history at selected layers are observed. These stress and strain time histories at a layer are used to generate stress-strain curves for each of the 30 ground motions for sand and clay columns. A typical stress-strain curve corresponding to ground motion of 1995 Kobe Port Island EQ is shown in Fig 3. In general, stress-strain curves are obtained from laboratory tests as a result of cyclic loading in the form of hysteresis loop. However, in the present analysis, stress-strain curve for each ground motion is a straight line obtained from equivalent linear analysis at the end of iterative process. Based on the slope of stress-strain curve, the value of G_{sec} and the corresponding value of Υ at a given soil layer is computed. For Fig 3, the value of G_{sec} and Υ are computed as 21900 kN/m^2 and 0.13% respectively. This exercise is repeated for all the 30 ground motions and 30 values of G_{sec} and Υ for each soil layer are obtained. The maximum value of G_{sec} amongst all the above 30 G_{sec} values is identified as G_{max} and the value of G_{sec}/G_{max} is obtained versus the value of Υ. Fig 4 presents a typical G_{sec}/G_{max} curve for sand column obtained from above steps corresponding to an overburden thickness of 1m. It has to be highlighted here that one set of G and the corresponding Υ are obtained from one ground motion. Above calculated $G_{sec}/\ G_{max}$ are then compared with the standard $G_{sec}/\ G_{max}$ curve used as input in the analysis as shown in Fig 4. Similarly, for clay column, Fig 5 presents the comparison between estimated G_{sec}/G_{max} and standard G_{sec}/G_{max} curve at 2m. Collectively, it can be

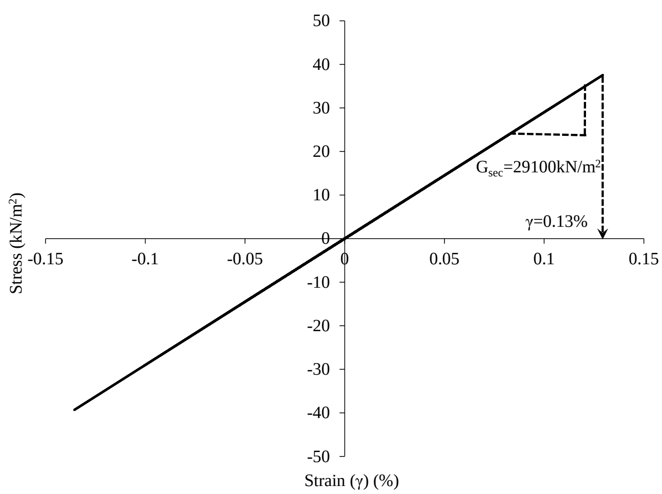

Fig 3- Determination of G_{sec} and γ from stress-strain curve in clayey soil

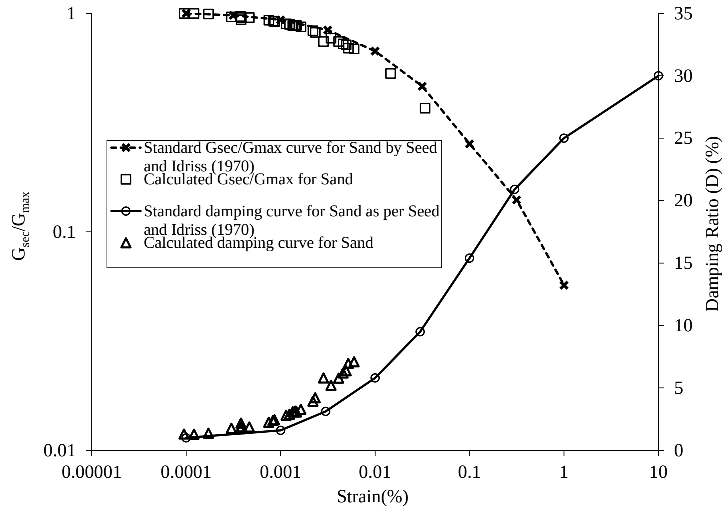

Fig 4- Comparison of calculated G_{sec}/G_{max} and damping curve with the standard curves for sand at 1m depth

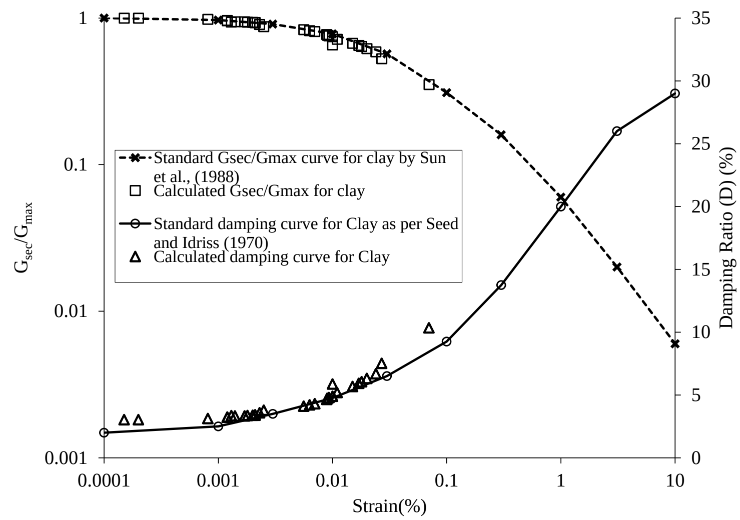

Fig 5- Comparison of calculated G_{sec}/G_{max} and damping curve with the standard curves for clay at 2m depth

observed from Fig 4 and Fig 5 that estimated G_{sec}/G_{max} curves obtained by summing the responses of same soil corresponding to 30 ground motion records obtained from equivalent linear analysis, both in case of sand as well as clay are matching closely with the G_{sec}/G_{max} curves which is nonlinear soil property used as input for the analysis. Another dynamic soil property i.e. D on the other hand, can be calculated based on the area under hysteresis loop. In the present work however, obtained stress-strain curve for each EQ ground motion is in the form of a straight line with no actual hysteresis loop (see Fig 3). Thus, the value of D cannot be estimated directly from the above obtained stress-strain curve. For this reason, the value of D is calculated from G_{sec}/G_{max} corresponding to each ground motion using following empirical correlations;

$$D(\%)=0.33[0.586(G_{sec}/G_{max})^2-1.547(G_{sec}/G_{max})+1] \quad \text{(For sand by [17])} \tag{1}$$

$$D(\%)=17.83[0.56(G_{sec}/G_{max})^2-1.39(G_{sec}/G_{max})+1] \quad \text{(For clay by [18])} \tag{2}$$

Where, G_{sec}/G_{max} are the estimated values from the stress-strain curve for each ground motion as discussed earlier. It has to be highglighted here that the value of D obtained from each of the above equations is corresponding to same value of ϒ obtained in G_{sec} determination from each ground motion. This way D versus ϒ is estimated for sand and clay columns considering all the 30 ground motions. Fig 4 and Fig 5 also present comparison of the collective D versus ϒ curve obtained above considering all the 30 ground motions with standard damping curves for sand and clay columns respectively used as input in the analyses. It can be observed from Fig 4 and 5 that similar to G_{sec}/G_{max} comparison, even the estimated damping curves for sand and clay are very closely matching with the standard damping curves used in the analysis for considerable range of ϒ. Comparison presented in Fig 4 and 5 are clear indication that dynamic soil properties of soil which defines nonlinear soil behaviour can be approximated as summation of equivalent linear soil behavior over large set of ground motions covering wide range of ground motion characteristics. In other words, nonlinear soil hebavior is the summation of equivalent linear soil behaviors over a range of strains. It has to be highlighted here that empirical correlation given in equation 1 is applicable only till a ϒ of 0.01. For this reason, no value of damping for sand are shown for ϒ >0.01 in Fig 4. Further, based on Fig 4 and 5 it can be observed that the values of G_{sec}/G_{max} and D which controls the soil behavior is a function of one value of ϒ develop by each particular ground motion in that particular soil layer. In other word, if this value of ϒ is known, the response of the soil layer can be determined by using one value of G_{sec}/G_{max} and D corresponding to above ϒ, avoiding present iterative procedure followed in equivalent linear approach. Thus, in the next step, two empirical correlations to determine the value of ϒ for sand and clay based on the above analyses are attempted.

The amplitude of ground motion controls the level of ϒ generated in the soil layer. Kumar et al [1] clearly highlights the fact that in case ground motion having high PHA is used as input, it will generate high ϒ in the soil layer. The response of soil layer in such a case will be governed by low value of G_{sec}/G_{max} and higher value of D which are soil properties at high ϒ [1]. Similarly, in case ground motion having lower PHA motions is used as input, the soil response in this case will be governed by high value of G_{sec}/G_{max} and low value of D which are soil properties at low ϒ [1]. Thus, a soil will experience low value of ϒ when subjected to low PHA and high value of ϒ when subjected to high PHA. Similar to PHA of input motion, another parameter which may control the level of ϒ in a specific soil layer is the depth of that particular soil layer below the free surface i.e. the overburden thickness (H). Since in the available ground response tools, the value of ϒ is calculated based on layer thickness, to make present approach consistent with available tool, the change in ϒ is studied against change in H and not the overburden pressure. To illustrate the effect of H, the stress-strain behavior of earlier used sand column is observed corresponding to H of 5m as shown in Fig 6. While Fig 3 shows minimum and maximum values of ϒ as 0.000095% and 0.033% respectively corresponding to H of 1m, Fig 6 shows minimum and maximum values of ϒ as 0.000478% and 0.112% respectively. Thus, in comparison to sand available at 1m depth, sand available at 5m depth is experiencing higher values of ϒ. Similar observations are made in case of clay column as well. While clay at 2m depth is experiencing máximum and mínimum values of ϒ as 0.00015% and 0.07% as shown in Fig 4, Fig 7 shows mínimum and máximum strains of 0.0008% and 0.19%

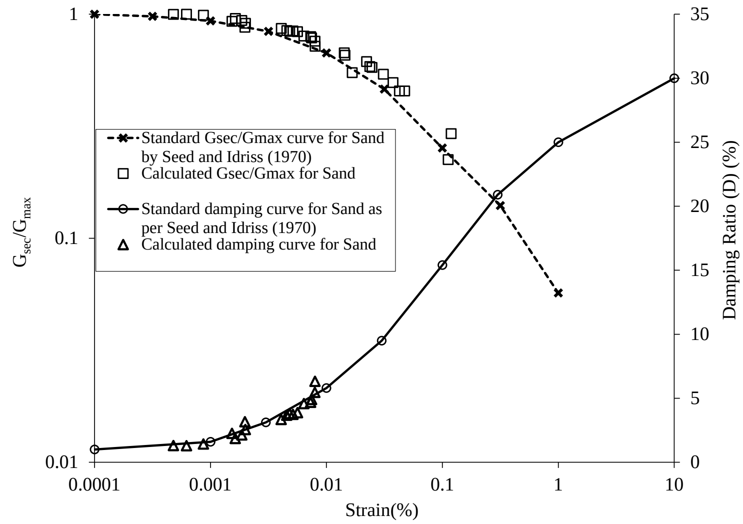

Fig 6- Comparison of calculated G_{sec}/G_{max} and damping curve with the standard curves for sand at 5m depth

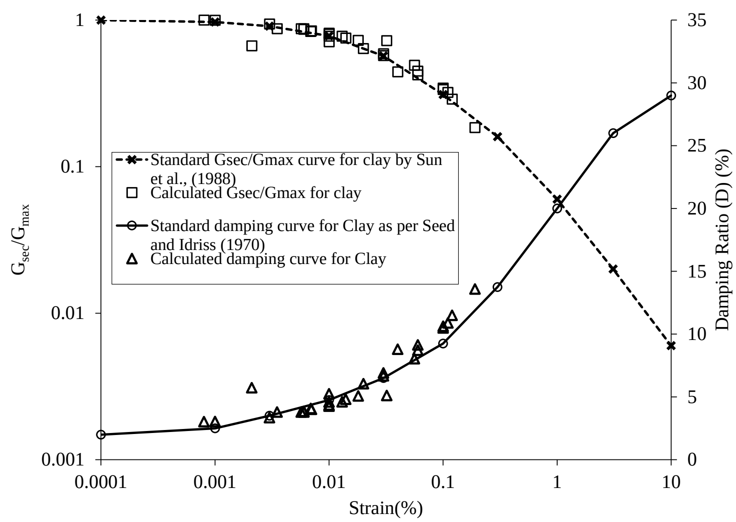

Fig 7- Comparison of calculated G_{sec}/G_{max} and damping curve with the standard curves for clay at 6m depth

respectively which the clay at 6m is experiencing. Based on the observation made from Fig 4, 5, 6 and 7 it can be concluded that in addition to PHA of input motion, H is another parameter which controls the level of ϒ in sand and clay. Change in the values of ϒ with respect to PHA as well as H are observed for the above considered sand and clay columns as shown in Fig 8 and 9 respectively. From Fig 8 it can be observed that with the increase in H, the value of ϒ increases. Similarly, for same value of H, the value of ϒ also increases with increase in PHA of ground motion. Similar observations can be made from Fig 9 in case of clay column. Based on the variation pattern in the value of ϒ with H and PHA, two empirical correlations are proposed following step by step regression analysis for sand and clay as;

$$\gamma(\%)=(0.0146PHA-0.0007)\exp^{(0.5H)} \quad \text{(For sand)} \quad (3)$$

$$\gamma(\%)=(0.019H+0.140)PHA+0.002H-0.014 \quad \text{(For clay)} \quad (4)$$

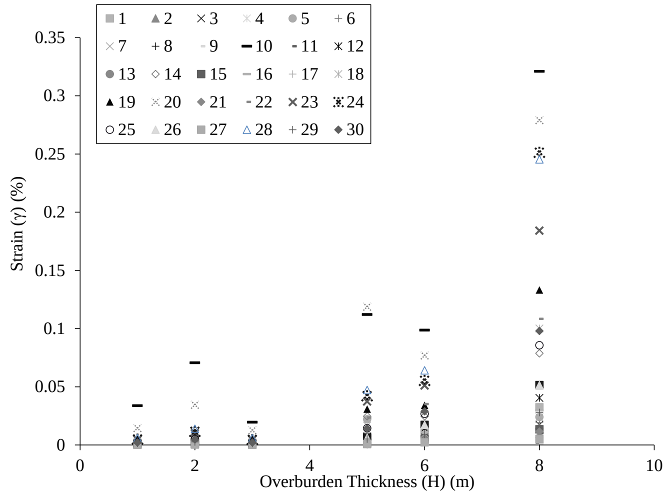

Fig 8- Variation of strain with overburden thickness and PHA for sand

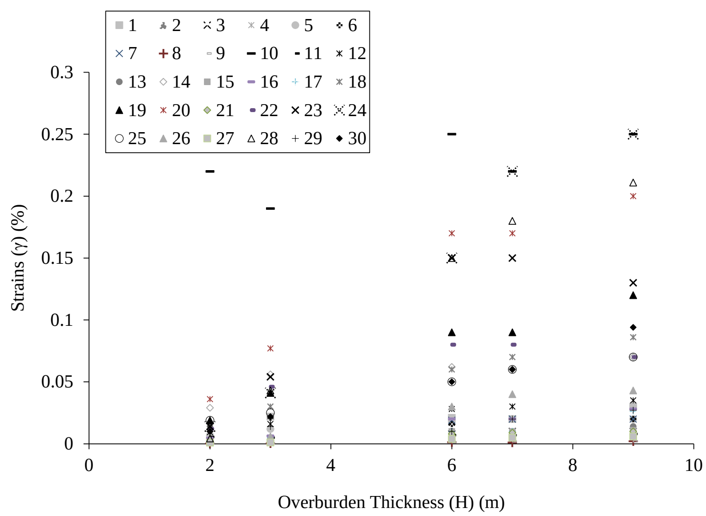

Fig 9- Variation of strain with overburden thickness and PHA for clay

The functional form of each of the above equations is chosen based on least square approach. Using the proposed correlations above, for a known value of PHA obtained from seismic hazard analysis as well as the H obtained from borehole data, the value of ϒ can be determined. In case the values of G_{sec} and D at this value of ϒ are known, a one-step equivalent linear analysis can be done since the soil behavior will be controlled by the above value of ϒ.

6. Conclusion

Presence of local soil can enhance the amount of damages during an EQ even at larger distances. Site response analysis helps in understanding the possible change of ground motion characteristics between the bedrock and the surface due to the presence of local soil. Two important components of any site response analysis are input bedrock motion as well as dynamic soil properties. In the absence of regional ground motion records, the problem of input motion can be avoided by selecting a large number of ground motions with varying ground motion characteristics. However, in the absence of regional G_{sec}/G_{max} and damping curves for the soil under study, standard G_{sec}/G_{max} and damping curves are used in addition to *in-situ* soil properties. Present work analyzed 15m sand and clay columns corresponding to 30 globally recorded ground motions following equivalent linear approach. Based on the present analyses, it is found that each ground motion induce one level of ϒ is a soil layer. If the response of same soil layer is observed during wide range of ground motions, a complete understanding of nonlinear soil behavior can be developed from equivalent linear analyses. Further, above value of ϒ developed in a soil layer is a function of PHA of input motion as well as the overburden thickness for that layer. Based on the present analyses, two empirical correlations are proposed which can be used to determine above value of ϒ for sand and clay alone. Once, the value of ϒ is known, the soil response can be understood based on one value of G_{sec}/G_{max} and low value of D avoiding iterative procedure. Based on seismic hazard analysis, the value of PHA can be estimated. Thus, knowing the depth os particular soil layer, the value of ϒ governing the soil layer behavior can be determined. This way accurate estimation of soil bahevior can be done. Further, it has to be highlighetd here that present work proposed correlations for complete deposit of sand and clay. However, in practical condition, often a soil deposit is found with layers of different material types along the depth. In such cases, observations made in this work will be applicable. However, correlation similar to the one present in this work can be developed depending upon subsoil conditions and following above discussed methodology.

7. Copyrights

8. References

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